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EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND


## THE BLENDED-LIGHT LAMP
### AND OTHER MERCURY LAMPS WITH IMPROVED COLOUR RENDERING

by E. L. J. MATTHEWS. 621.327.3 : 621.327.9

Compared with ordinary electric lamps gas-discharge lamps have the advantage of a much higher efficiency; for certain applications, however, they have the disadvantage that the colour of the objects illuminated deviates disturbingly from that by daylight. In this article the methods are examined by which this objection can be met in the case of high-pressure mercury lamps. There are two methods which may be considered: the application of fluorescent substances, and the blending of mercury light with the light of ordinary electric lamps. The first method led to the development of mercury lamps with fluorescent bulbs, the second to the design of fixtures for blended light and to the development of a blended light lamp which combines incandescent lamp and mercury lamp in one system. The degree to which the light sources obtained approach daylight is studied by means of the block method.

Upon the appearance of metallic vapour lamps which were suitable for practical use it was to be expected that the pronounced colour of the light of these lamps and the resulting unnatural colour of the illuminated objects would prevent the unrestricted application of this type of light source. Since, however, the unusually high efficiency made their use very attractive, means have been sought of improving their colour rendering.

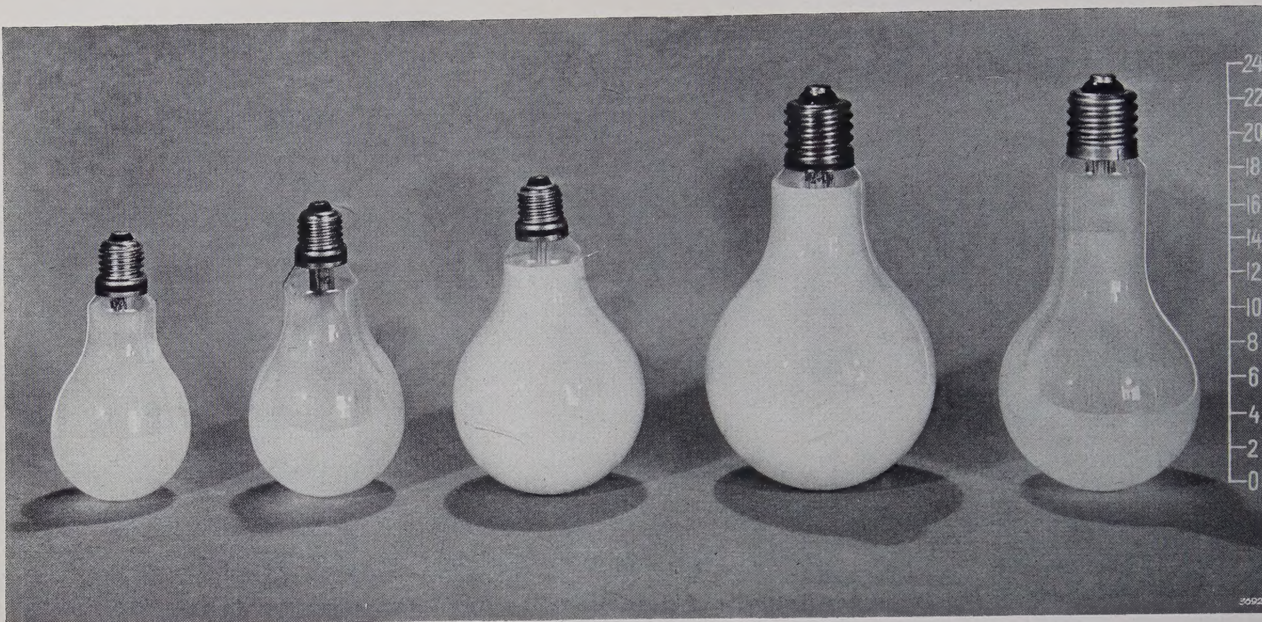
In an earlier article in this periodical [1]) the method was discussed by which "white" light [2]), *i.e.* light which makes a satisfactory colour rendering possible, can be obtained with tubular luminescence lamps of low mercury pressure. We shall here examine the method by which the same problem can be brought to a satisfactory practical conclusion in the case of high-pressure mercury lamps.

For this purpose several new types of lamps were developed from the high-pressure mercury lamp, particularly the high-pressure mercury lamp with luminescent bulb (HPL) and the blended light lamp (ML), the latter of which combines a filament and a mercury discharge tube in one bulb. Before dealing with these lamps and the way in which white light can be obtained with the lamps alone or in combination with incandescent lamps, we shall first discuss briefly the properties of the high-pressure mercury lamp itself.

### High-pressure mercury lamp, type HP

In the first volume of this periodical [3]) the high-pressure mercury lamp HP 300 was described which differed from the earlier low-pressure mercury lamps by its greater efficiency, its extremely small size and its low electrical power consumption (75 W), which made it possible to use the lamp for indoor illumination also. With the same consumption and providing the same light flux (3 000 lm), a new type of lamp has since been developed which, in different models, has found increasing application within the last few years. This lamp differs from its predecessor chiefly by its lower ignition and burning voltage, which for 220 V mains voltage makes it possible to replace the leakage transformer formerly needed by a choke, which is cheaper and which, moreover, causes fewer electrical losses. As to the external appearance of the lamp, this also made it possible, thanks to the lower working voltage, to replace the special base with pins by an ordinary Edison or Swan base, which did much to promote the use of the new lamp. In the ordinary model the bulb is inside-frosted. The base is provided with a green ring as a warning

[1]) Philips techn. Rev. **4**, 337, 1939.
[2]) Philips techn. Rev. **2**, 1, 1937; **4**, 66, 1939.
[3]) Philips techn. Rev. **1**, 129, 1936.




*a* *b* *c* *d* *e*

Fig. 1. The high-pressure mercury lamps HP 300, HP 500, HPL 300. HPL 500 and the blended-light lamp ML 500. The HPL lamps have a bulb which is covered on the inside with a layer of a fluorescent material, the blended-light lamp ML 500 contains, in addition to the mercury discharge tube, a filament which provides half the total light flux. To the extreme right a cm scale. The first three lamps have an Edison base and are also made with Swan base; the last two lamps have a Goliath base.

that the lamp may not be screwed into any socket but only in a special holder which is part of a circuit containing a suitable series apparatus. This measure is especially important when mercury lamps and incandescent filament lamps are used at the same time, as for instance in the fixtures for blended light mentioned later. In such cases it is best, if possible, to use mercury lamps and ordinary lamps with different bases.

In addition to this new iamp, which has kept the old type number HP 300, a somewhat larger type HP 500 of 120 W, 5 000 lm is also manufactured. The action of these two lamps corresponds almost exactly with that of the previously described high-pressure mercury lamp, except for the fact that the ignition voltage is now lowered by an auxiliary electrode which, inside the lamp itself, it connected to one of the main electrodes *via* a current-limiting resistance.

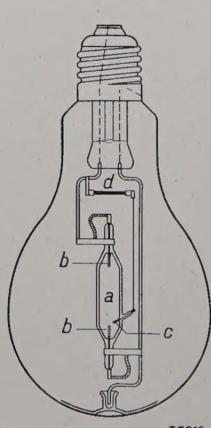


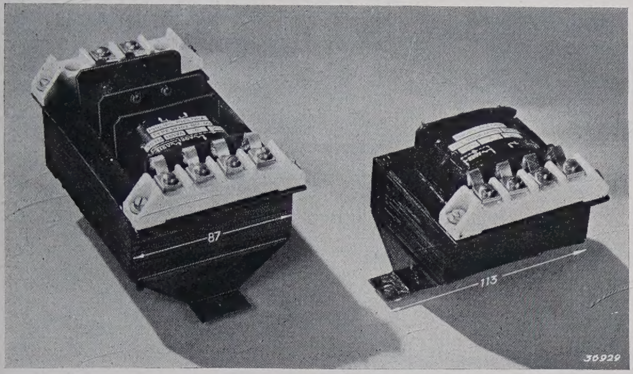

Fig. 2. The mercury lamp HP 300. In the discharge tube *a*, in addition to the main electrodes *b*, there is an auxiliary electrode *c* to one side, which is connected with one of the main electrodes *via* a resistance *d*.

*Figs. 1a* and *b* show these two types of lamp while in *fig. 2* a cross section is given of the mercury lamp HP 300. In *table 1* the most important data are given. The starting time, *i.e.* the time necessary for the lamp to reach its normal working state, is several minutes. During this time the power consumed and the light flux developed increase gradually. After switching off, the lamp must first cool for several minutes before being able to ignite again. This peculiarity limits the use of the lamp to cases where it is unnecessary to switch the lamp on and off in rapid succession.

**Table 1.** Properties of HP lamps.

| | HP 300 | HP 500 |
|---|---|---|
| light flux | 3 000 lm | 5 000 lm |
| consumption (lamp alone) | 75 W | 120 W |
| losses in choke (220 V A.C. mains) | 8 W | 12 W |
| ditto with leakage transformer (115—125 V A.C. mains) | 17 W | 23 W |
| efficiency with choke | 36 lm/W | 38 lm/W |
| ditto with leakage transformer | 32.5 lm/W | 35 lm/W |
| starting time | 4-5 min | 4-5 min |

The latest models of the series apparatus, over which the HP lamps must be connected, are of such small dimensions that no difficulty is experienced in building them into fittings, etc. *Fig. 3* shows the choke coil (220 volt mains) and the leakage transformer (115-125 volt mains) for the mercury lamp HP 300. The corresponding appliances for the mercury lamp HP 500 are about 1 cm higher.




*a* *b*

Fig. 3. Series apparatus for the mercury lamp HP 300: *a*) leakage transformer for mains of 115-125 V. *b*) choke coil for 220 V mains. The corresponding apparatus for the mercury lamp HP 500 are 14 and 12 mm higher, respectively (113 mm is not the width of the core, but the total width of the choke coil including the feet).

The light of the HP lamps consists mainly of the well-known yellow, green and blue-violet mercury lines with a very weak continuous background (*fig. 4*). The use of these lamps with no colour correction will as a rule result in a pronounced colour change of the illuminated objects.

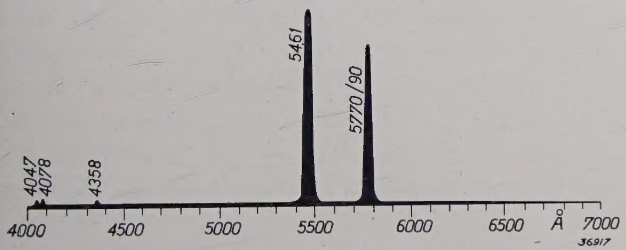



Fig. 4. Spectral distribution of the light of the high-pressure mercury lamps HP 300 and HP 500.

Nevertheless an extensive and varied sphere of use for these lamps has grown up, partly in spite of the peculiar colour of the light, in cases where the high efficiency is the deciding factor, and partly just because of that colour or of other properties of the light such as the greater acuity of vision which can be attained with mercury illumination [4]). HP lamps are widely used for public lighting in cities or for general illumination in the metal industry, while they are also used with great success for the illumination of white or coloured advertising signs and for flood lighting lawns or groups of trees which assume an especially natural appearance in this light because of the high content of green radiation in the mercury light. Applications based upon improved colour contrast are found in the illumination of coal sorting belts where the mercury light increases the contrast between coal and stone, or in the marking department of construction workshops and plate workshops, where the lines drawn with a copper stylus on the iron come out very clearly in the mercury light. Surface flaws in tin plate, nickel plate or chromium plated objects, on enamelled products, on porcelain, on glossy paper are more easily observed by the light of HP lamps than by ordinary white light. The inspection of plate glass before it is placed in the cooling ovens is based not only upon colour contrast but also upon visual acuity. In conclusion the use of HP lamps in photographic enlarging apparatus [5]) may be mentioned.

**High-pressure mercury lamp with colour correction, type HPL**

The colour rendering of the HP lamps, which is inadequate for ordinary purposes, has been improved in different ways. In the first place it is possible to cover the inside of the bulb of the HP lamp with a layer of fluorescent material. In this fluorescent layer the conversion into light takes place of the ultra-violet radiation which is excited in the mercury discharge and which is otherwise lost by absorption in the glass of the bulb. The fluorescent material, which gives a continuous spectrum, is so chosen that as much red light as possible is obtained upon conversion, which red light is entirely missing in the natural mercury light. This brings about a very considerable colour correction. The light flux hereby remains unchanged: the fluorescence light approximately compensates for the loss of primary mercury light which is absorbed in the fluorescent layer. Electrically also the lamps with fluorescent bulb HPL 300 and HPL 500 (fig. 1*c* and *d*) are exactly like the mercury lamps HP 300 and HP 500, respectively. The bulb of the HPL lamps is made slightly larger than that of the HP lamps since this makes the efficiency of the fluorescent layer higher.

Although important, the colour correction in the HPL lamps is nevertheless not such that the lamps can be recommended for every use: they do not

[4]) Philips techn. Rev. **1**, 215, 1936.

[5]) Philips techn. Rev. **3**, 91, 1938.

give "white" light. This could hardly have been expected since the available quantity of ultraviolet radiation in the discharge, even with the optimum conversion efficiency, is insufficient to provide a complete colour correction. The HPL lamps are nevertheless suitable for all cases where it is unnecessary to be able to determine accurately the finer shades of colour. They can therefore be used for street lighting as well as for factories, workshops, garages, storerooms, etc. For photography on extra red-sensitive panchromatic material the HPL lamp may also very well be used and even gives an extraordinarily faithful reproduction of the colour relations [6]).

**Blended light of mercury and incandescent filament lamps**

For cases in which the HPL lamp is unable to render the colour gradation satisfactorily, the mercury light may be blended with ordinary electric light. There are special fixtures for this purpose, for interior lighting (*fig.* 5) as well as for use out


Fig. 5. Blended-light fitting. Enamelled reflector for workshop illumination, containing three ordinary electric lamps and one mercury lamp.

of doors. In the blended light thus obtained the excess of red rays from the electric lamp serves to make up the corresponding shortage in the light of the mercury lamp. By a well chosen construction of the fixture and a correct relative arrangement of the different lamps, a satisfactory blending of the two kinds of light can be obtained without the formation of coloured shadows. An extra advantage of this blended light is, that upon switching on, a large part of the normal light flux is immediately available, namely that part which is due to the incandescent lamps. Upon repeated switching on also, it is unnecessary to wait for the mercury lamp to cool, since the filament lamps are always ready for action. In order to obtain a better blending of the two kinds of light it is necessary to divide the total amount of ordinary electric light necessary per mercury lamp over a number of small lamps. The proportions of the mixture can then be adapted to the needs of each case. When no particular requirements are made the proportions 1 : 1 will be satisfactory. *i.e.* a mixture consisting of equal quantities of the two kinds of light. In practice this can be attained for instance with one HP 300 or HP 500 and one or more electric lamps with a total consumption of 200 or 300 watts, respectively. If higher requirements are made of the colour rendering, the content of ordinary electric light will often have to be increased. Conversely, the percentage of ordinary electric light can be decreased when the colour rendering is not the primary requirement, but, for instance, visual acuity, or when the objects being observed are mainly white. If it is desired to suppress the violet light of the mercury lamp, which gives blue objects especially an unnatural appearance, it is best to replace the HP lamp by an HPL lamp, or to use a suitable yellow-green filter around the mercury lamp. So little light need be absorbed by the glass of the filter that the total efficiency of the lamp is scarcely affected by it. This is due to the fact that the violet radiation in the mercury light comprises less than 1 per cent of the light flux.

When blended light is used the total efficiency of the combined light sources will necessarily be lower than that of the mercury lamps. Nevertheless it is always higher than that of ordinary electric lamps alone, and it is strikingly better than the efficiency of the so-called daylight blue lamps which were formerly used almost exclusively for a correct colour rendering, and which consist of ordinary electric lamps in a blue glass bulb. While the latter gave good results, it was only at the expense of a very low efficiency, and therefore in some cases of an unpleasant rise in temperature of their surroundings.

It would be difficult to give a survey of all the cases in which mercury blended light can be successfully used. As an indication therefore a few typical applications are given in *table 2* with the most important practical data referring to those uses. These can be varied according to taste and circumstances.

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[6]) Philips techn. Rev. 4, 27, 1939.

**Table 2.** Blended light of mercury and incandescent lamps.

| Application | Proportions of mixture $\frac{\text{lumen mercury light}}{\text{lumen incand. light}}$ | Remarks |
|---|---|---|
| **Show windows** | | |
| flowers | 1/2 | for light colours and green: mercury lamp HPL |
| textiles | 1/2 | preferably with yellow-green filter |
| gold | 1/1 | |
| zilver | 2/1 | |
| fancy goods | 2/1 | with yellow-green filter in some cases |
| bicycles, tools, stoves, etc. | 1/1 | |
| **Interior illumination** | | |
| general | 1/1 - 1/1.5 | indirect, if necessary |
| drafting rooms | 1/1 - 1/1.5 | indirect |
| offices | 1/1 - 1/1.5 | |
| exhibition halls | 1/1 - 1/1.5 | |
| printing offices: | | |
| hand composing room | 3/1 | |
| rotating press | 1/1 | |
| colour printing | 1/2 | indirect, mercury lamp HPL |
| offset | 1/1.5 | |
| binder | 2/1 | |
| shops (textiles) | 1/2 | |
| **Outdoor illumination** | | |
| streets | 2/1 - 1/1 | |

## Blended-light lamp, type ML

In a number of cases the use of blended light can be considerably simplified by the application of the new blended-light lamp ML 500. This lamp, which, except for the inside-frosting of the bulb, does not differ in appearance from an ordinary 300 W electric lamp (fig. 1*e*) combines in itself a mercury discharge tube and a filament, which are connected in series and placed in a bulb filled with the mixture of argon and nitrogen which is ordinarily used for electric lamps. The filament, which furnishes half of the total light flux of the lamp, also serves as a stabilizer for the discharge, so that the separate series apparatus which would otherwise be necessary may be omitted.

Since not only the filament, but also the mercury discharge in the blended-light lamp functions under conditions which deviate from the usual ones, we shall discuss them briefly. Upon ignition the mercury discharge has at first an arc voltage of about 15 volts, so that the filament must take up the whole difference between this voltage and the mains voltage. When burning normally, on the other hand, the voltage to be taken up by the filament is considerably lower. The filament is therefore heavily overloaded in the starting period, so much indeed that during the first minute after the lamp has been switched on it evaporates as much as during an hour of ordinary use. This periodic overloading of the filament while the discharge is starting results in the fact that the life of the blended-light lamp depends to a greater degree than is the case with most other light sources on the number of times it is switched on, or on the average length of burning after each time it is switched on. Furthermore it must be noted that the ever present fluctuations in the mains voltage are transmitted entirely to the filament, since the arc voltage of the mercury discharge tube is constant in normal use. The result is that the percentage of fluctuations for the filament, which takes up only a part of the mains voltage, will be considerably higher than that for the whole lamp. In connection with this it is absolutely essential that the blended-light lamp be used at the correct mains voltage.

As concerns the mercury-discharge tube, it here acts in series with the ohmic resistance of the filament, instead of with the inductive resistance of a choke coil. The lag of the current is thus eliminated which is due to the inductive resistance in series with the lamp, and the result is an increase in the "re-ignition voltage" in the following half cycle. If the current lags in phase behind the voltage, then at the moment when the current changes from the positive to the negative direction there is already a considerable negative voltage, so that the lamp can immediately re-ignite. If, however, current and voltage have the same phase, at the moment when the current direction changes the voltage is zero, and it is a fraction of the following half period before the voltage has reached the re-ignition value. In this short time, however, the ionization in the tube falls back so that the re-ignition voltage increases.

The filament as well as the gas-discharge tube therefore work under less favourable conditions than if they were connected separately to the mains, and the result is that the efficiency of the blended-light lamp is somewhat lower than that of a corresponding combination of incandescent lamps and mercury lamps. Compared with blended light obtained from a mercury lamp and one or more incandescent lamps, however, the blended-light lamp offers the advantage of requiring no series apparatus. Furthermore it is important that the blended-light lamp burns with full light intensity immediately after being switched on, since the overloaded filament gives slightly more light at the moment when it is switched on than filament and mercury dis-

charge together in the normal working state. A third advantage of the blended-light lamp is that the starting time of the mercury discharge, which is about 5 minutes with the HP lamps, could be reduced to about 1 minute, by allowing the heat development of the filament to serve for the evaporation of the mercury.

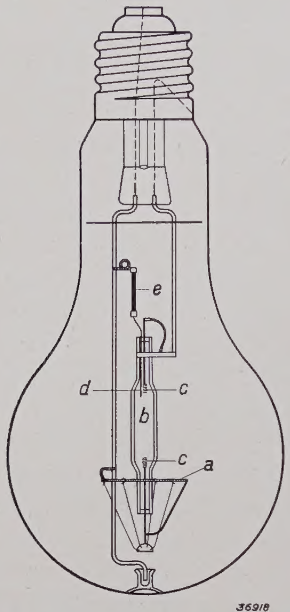


Fig. 6. Construction of the blended-light lamp ML 500. *a* filament in argon-nitrogen mixture, *b* mercury discharge tube, *c* main electrodes, *d* auxiliary electrode, *e* current-limiting resistance.

Like the other ordinary metallic vapour lamps, the blended-light lamp is intended for use on alternating current. The lifetime is calculated for an average of 2 000 hours, with the assumption that the average duration of burning after every switching on amounts to about 3 hours. The lamp is easily proof against mains voltage fluctuations of $\pm 5$ per cent, while the mains voltage may fall to 170 volts without the lamp being extinguished. The relative positions of discharge tube and filament as shown in *fig. 6* ensure a very good blending of the light, so that the lamp exhibits a completely uniform appearance. The most important practical data of the lamp are collected in *table 3*.

**Table 3.** Properties of the blended-light lamp ML 500

| | mercury discharge | filament | total |
|---|---|---|---|
| light flux | 2 500 lm | 2 500 lm | 5 000 lm |
| power consumption | 65 W | 185 W | 250 W |
| voltage | 78 V | 156 V | 220 V |
| current | | 1,19 A | |
| starting time | | 1 min | |
| cooling time *) | | 1-2 min | |

*) Within this interval of time after switching off it is impossible to re-ignite the lamp. The cooling time depends upon the circumstances.

The blended-light lamp ML 500 is still too new to have been able to conquer all the territory which it deserves. It may, however, be assumed that before long it will find its way into public lighting systems, while furthermore it should be considered for factories, offices, shops, warehouses, hospitals, churches, schools, theatres, halls and many other large covered spaces where larger lamp units are desired for the illumination.

### Spectral data of the different kinds of light

In addition to the method of trying by practical experiments to find the most suitable composition of the light which is to be used for a given type of illumination, there is the block method [7]). According to the latter method the entire visible spectrum is divided into 8 adjacent regions (see *table 4)*. Different lamps can then be compared with each other block by block with respect to the colour of the light. Two light sources will give practically the same colour gradation when the light fluxes in corresponding blocks are equal, or in a constant ratio to each other, notwithstanding the actual spectral distribution within the blocks themselves. The eye is, however, incapable of observing deviations from the colour equality defined in this way which are smaller than 10 to 25 per cent, or at least it is incapable of finding them disturbing. Sometimes a deviation in a given block can more or less compensate an opposite deviation in the adjacent block, especially when the colour difference between such blocks is not too great. On the other hand this tolerance will be found too great when two neighbouring blocks exhibit deviations in the same sense.

The kinds of light mentioned in table 4 are all compared with average daylight which is set equal to 1 in each block. In order to approach average daylight as closely as possible a given kind of light must therefore be represented in each block by a number differing as little as possible from one. At first glance the table seems to give little hope. A comparison with universally familiar kinds of light, however, (direct sunlight or electric light) shows how far one may deviate from the requirement without obtaining an illumination which is unnatural or unpleasant in colour. This is true at least as long as the spectrum exhibits no great lack of balance. In an otherwise satisfactorily uniform

[7]) See the articles referred to in footnote [2]).

**Table 4**

Light flux of various sources of white light in certain blocks of the spectrum; values for daylight set equal to unity.

| Blocks (boundaries in Å) | 4 000 | 1 | 4 200 | 2 | 4 400 | 3 | 4 600 | 4 | 5 100 | 5 | 5 600 | 6 | 6 100 | 7 | 6 600 | 8 | 7 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| average daylight | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| sunlight | | 0.64 | | 0.69 | | 0.70 | | 0.83 | | 0.96 | | 1.06 | | 1.16 | | 1.30 | |
| incandesc. electr. lamp ("Bi-arlita") | | 0.19 | | 0.20 | | 0.25 | | 0.48 | | 0.80 | | 1.17 | | 1.79 | | 2.60 | |
| "Daylight blue lamp" | | 0.35 | | 0.36 | | 0.44 | | 0.68 | | 0.97 | | 1.09 | | 1.18 | | 1.40 | |
| HP lamp | | 0.68 | | 3.19 | | 0.10 | | 0.08 | | 1.26 | | 1.26 | | 0.07 | | 0.09 | |
| ditto with yellow-green filter | | 0.37 | | 2.34 | | 0.06 | | 0.08 | | 1.37 | | 1.14 | | 0.10 | | 0.09 | |
| HPL lamp | | 0.29 | | 0.88 | | 0.16 | | 0.14 | | 1.14 | | 1.31 | | 0.41 | | 0.41 | |
| HP-blended light 2 : 1 | | 0.52 | | 2.19 | | 0.15 | | 0.21 | | 1.11 | | 1.23 | | 0.65 | | 0.91 | |
| ditto 1 : 1 *) | | 0.44 | | 1.69 | | 0.17 | | 0.28 | | 1.03 | | 1.22 | | 0.93 | | 1.33 | |
| ditto 1 : 2 | | 0.36 | | 1.24 | | 0.20 | | 0.39 | | 0.95 | | 1.20 | | 1.21 | | 1.74 | |
| HPL-blended light 1 : 2 | | 0.24 | | 0.42 | | 0.19 | | 0.37 | | 0.91 | | 1.21 | | 1.33 | | 1.86 | |
| HP-blended light 1 : 2 with yellow-green filter around mercury lamp | | 0.26 | | 0.92 | | 0.19 | | 0.35 | | 0.99 | | 1.16 | | 1.22 | | 1.74 | |

*) Blended-light lamp ML 500

spectrum, for example, one stronger spectral line, especially when it belongs to the blue-violet part of the spectrum, can make the light in question entirely unsuitable.

The spectrum of the HP lamp, which actually consists of lines (fig. 4), has a very irregular appearance. There can be no question of any analogy with average daylight. In the case of the HPL lamp this irregularity is much reduced, the excess of blue-violet is removed, but the red is not sufficiently reinforced. The HP lamp with yellow-green filter lies between the two preceding ones as concerns these colours which present the greatest difficulty for every mercury lamp.

The different kinds of mixed light form, according to the table, so many compromises between an optimum red rendering and the best possible blue rendering. According as the incandescent lamp light in the HP blended-light makes up a larger portion, the emphasis may be seen to shift from blue to red. The HPL blended light in the proportion indicated is found to possess a blue radiation relatively uniformly distributed over the first three blocks, but which is relatively too weak, so that the rendering of blue seems somewhat faded, while the red is rather reinforced and vitalized. The HP blended light with a yellow-green filter over the mercury lamp is especially remarkable for its excellent rendering of blue, and the red remains about as with the ordinary HP mixed light without filter in the same ratio.

This all agrees entirely with practical experience, where, according to the needs of every separate case, the emphasis may now be placed upon the red end of the spectrum, and then again on the blue end, thanks to the flexibility of the mixed light, so that a whole series of variants with respect to the composition is formed. It is therefore clear that with the help of blended light when used with judgment, not only with respect to the system chosen but also with respect to the proportions of the mixture, more satisfactory results can be obtained than with ordinary electric light alone.

# AN ELECTRICAL PRESSURE INDICATOR FOR INTERNAL COMBUSTION ENGINES

by P. J. HAGENDOORN and M. F. REYNST.

531.787.9 : 621.43

In order to satisfy the severe requirements made of the indicator for measuring the pressure in modern internal combustion engines an electrical measuring apparatus (pressure indicator, type GM 3 154) has been developed which employs a cathode ray tube. A membrane is set into the wall of the cylinder, and together with an opposing electrode forms a condenser. The condenser is part of a bridge connection which is fed with a high frequency voltage. When the capacity of the membrane condenser varies due to the movement of the membrane, the high-frequency voltage taken from the bridge is modulated with these variations, which form a picture of the variations in pressure. After amplification and rectification the deflection voltage is obtained for the vertically deflecting plates of the cathode ray tube. The horizontal deflection can be made proportional to the time as well as to the displacement of the piston. The construction of the indicator on this principle is discussed and the most important details are explained.

The classical device for controlling the functioning of steam engines and internal combustion engines is the mechanical pressure indicator which traces the pressure in the cylinder as a function of the position of the piston. In this way a pressure volume diagram is obtained (*fig. 1*), from which conclusions may be drawn about the different processes taking place in the cylinder, and from which by planimetry the work done by the burning gas per revolution of the crank shaft (the "indicated power") can directly be determined.

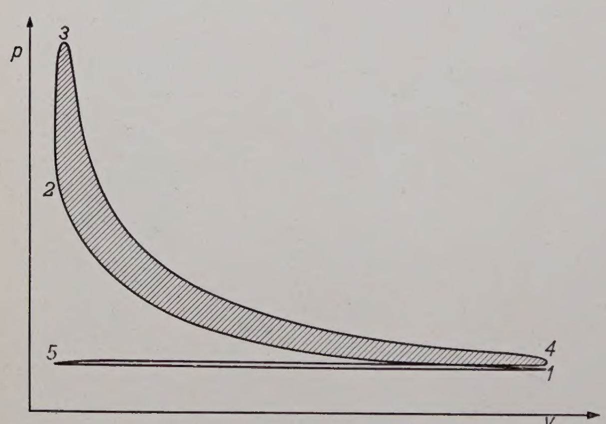


Fig. 1. Normal appearance of the pressure-volume diagram of a four-stroke internal combustion engine. Upon movement of the piston from *1* to *2* the air in the cylinder is compressed, at *2* the fuel (oil) is sprayed in, a moment later the mixture begins to burn and the pressure rises quickly to the peak value at *3*. From *3* to *4* the gas expands. Upon the following stroke of the piston the burned gas is driven out (*4* to *5*) and fresh air sucked in (*5* to *1*), whereupon the process begins anew. The shaded area indicates the work done by the cylinder during two revolutions of the crank shaft.

The new engine constructions of the last 10 or 20 years, which work at higher speeds of revulution (up to 6 000 r.p.m. in aeroplane engines) and involve a heavier loading of the material than was formerly the case, on the one hand make an indication of the pressures prevailing more necessary, and on the other hand they make heavier requirements of the indicating instrument. This instrument must be adapted to the higher speed of revolution mentioned, and furthermore a single diagram will often not be sufficient, but a continuous indication during operation will be desired, while at the same time the fine details of the diagram will be more important than formerly, such as those which correspond to the moment when the fuel is sprayed in and to the progress of the combustion of the gas mixture.

As has often been affirmed in this periodical, in the investigation of such mechanical phenomena where higher frequencies are concerned electrical methods of measurement offer great advantages over mechanical methods, since the cathode ray tube which can thereby be used as indicating instrument is practically free of time lag. A continuous indication can easily be obtained with this instrument, while at the same time the indicator can be situated at a central point where various phenomena — for instance the variation of the pressure in several cylinders — can be examined.

An indication of the pressure with the help of the cathode ray tube can be realized as follows. The pressure variations in the combustion chamber are converted into electrical voltage variations by means of a pressure indicator connected with the said chamber, which, as regards function, may be compared with a microphone. The voltage variations are amplified and fed to the set of plates for vertical deflection of a cathode ray tube. At the same time a voltage is applied to the plates for horizontal deflection which varies proportionally to the displacement of the piston. On the fluorescent screen of the tube the above-mentioned pressure-volume diagram appears. If, as is more usual in oscillography, the horizontal deflection voltage is allowed

to vary proportionally to the time, a pressure-time diagram is obtained which may sometimes also be useful.

The problems which are encountered in the realization of these principles, and the solutions which have been found in the pressure indicator (type GM 3 154) developed by Philips, will be discussed in the following. The realization of this pressure indicator and its adaptation to the requirements of internal combustion engines would have been impossible without the stintless collaboration of the Laboratory at Delft of the *Bataafsche Petroleum Maatschappij* and of the N.V. *Werkspoor* at Amsterdam who placed there experimental plant at our disposal and contributed to these experiments by word and deed.

## Principle of the arrangement

### *The pressure recorder*

In the pressure recorder an elastic deformation of some kind of body is caused by the variation in pressure. This deformation can give rise to an electrical voltage variation in various ways as in the different ordinary microphones [1]), namely by the piëzo-electric effect (crystal microphone), by a change in resistance (carbon microphone), by a change in capacity (condenser microphone) or by an electrodynamic or electromagnetic method (ribbon microphone). If it is required that the relation between voltage and change in pressure shall be independent of the frequency over a long range, only the first three methods mentioned can be considered, as is explained in the article already referred to [1]), with the additional condition that the (lowest) characteristic frequency of the body upon which the varying pressure acts must lie sufficiently far above the frequency range with which we are concerned. If we assume a maximum velocity of 9 000 r.p.m. (this has already been employed in test models of engines), then the fundamental frequency of the diagram to be recorded (with a two-stroke engine) is 150 c/s. In order to reproduce all the details of the diagram satisfactorily, such as the steepest pressure peaks, detonation vibrations, etc., the 20th harmonic must still show no appreciable change in amplitude and phase. It is therefore desirable [2]) that the resonance frequency of the recorder should be at least 8 times as high, *i.e.* at about 25 000 c/s.

In order to obtain satisfactory sensitivity with such a high characteristic frequency it is important to use for the pressure recorder a vibrating system with as small a mass as possible. In this respect the condenser microphone is particularly suitable: the vibrating mass here consists only of a thin membrane which is bent more or less by the pressure variations. Together with a rigid counter electrode in the shape of a plate, the membrane forms a condenser whose capacity varies with the movement of the membrane. The Philips indicator is constructed on this princple. *Fig. 2* shows diagrammatically how the membrane condenser can be built into the wall of the engine cylinder. For the sake of simplicity in fastening it, the membrane is earthed and the counter electrode insulated.

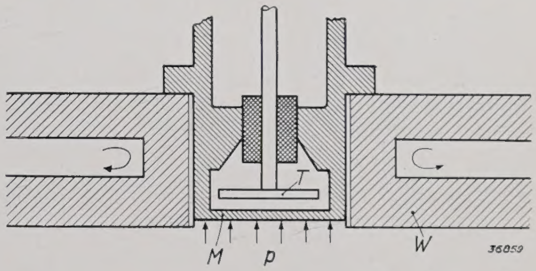


Fig. 2. The membrane $M$ which is fixed into the wall $W$ of the cylinder and which is moved more or less by the pressure $p$ in the cylinder, forms, together with the counter electrode $T$, a condenser of variable capacity.

### *The conversion of the capacity variations into voltage variations*

In the case of the condenser microphone the membrane condenser, which is charged by a direct current source, is included directly in the grid circuit of an amplifier valve. When the charge is kept constant the changes in capacity cause changes in the grid voltage which are then further amplified. For the pressure recorder, however, this connection, although simple in principle, cannot be considered. In this case it is also necessary to be able to measure unchanging pressures as well (this is especially important for the calibration), so that it would become necessary to use a D.C. amplifier. In many respects it is more difficult to use such an amplifier. Moreover very severe requirements which can hardly be satisfied are made of the insulation of the connection between the condenser and the grid of the first amplifier valve. In order to avoid these difficulties a quite different principle is applied in the Philips pressure indicator. The membrane condenser is included in a bridge circuit to which a high-frequency A.C. voltage is applied, see *fig. 3*. When the bridge is in equilibrium, there is no voltage between the points *c-d*. When the equilibrium is disturbed by a variation in capacity $\Delta C$ of the membrane condenser, a high-frequency A.C. voltage

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[1]) J. de Boer, Microphones, Philips techn. Rev. 5, 140, 1940.
[2]) See for example K. J. de Juhasz and J. Geiger, Der Indikator, Springer, Berlin 1938, p. 240.

acts between *c-d*, whose amplitude is proportional to $\Delta C$ when the variations are not too great. In this way a high-frequency voltage (carrier wave) is obtained which is modulated with the pressure changes to be recorded. From this, after amplification and rectification, the desired deflection voltage for the vertical deflection of the cathode ray is obtained.

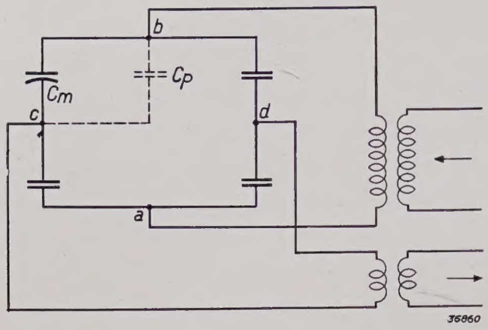


Fig. 3. The membrane condenser $C_m$ is included in a bridge connection. At *a-b* (*via* a cable and matching transformer) a high-frequency A.C. voltage is fed to the bridge. If the bridge is balanced for a given value of $C_m$, then upon a variation $\Delta C$ of the latter a high-frequency voltage with an amplitude approximately proportional to $\Delta C$ will act across the points *c-d*. This "modulated carrier wave" is taken off by a cable with matching transformer.

In *fig. 4* the main features of the whole circuit are given. The oscillator for the excitation of the carrier wave is built into a cabinet together with the amplifier, the cathode ray tube and several auxiliary apparatus, the bridge connections on the other hand are placed in the immediate neighbourhood of the membrane condenser for reasons which will be discussed later. The high-frequency voltage is applied to the bridge, or taken from it, with a cable which may have a length of for instance 10 m, or in some cases 50 m, in order to ensure the necessary freedom in setting up the indicating instrument.

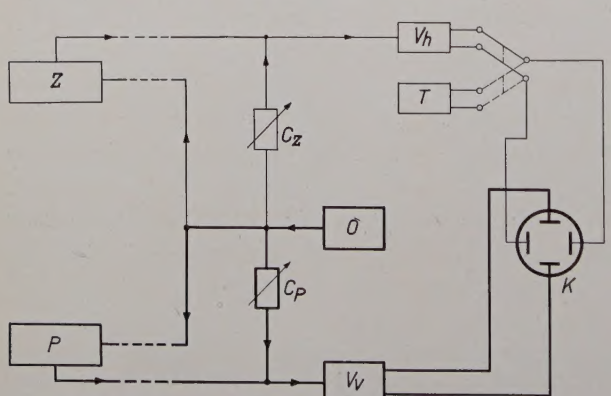


Fig. 4. Main features of the whole connection. *O* oscillator, *P* pressure indicator, $V_v$ amplifier for the vertical deflection voltage, *K* cathode ray tube, *Z* piston-stroke indicator, *T* time-base generator, $V_h$ amplifier for the horizontal deflection voltage. $C_p$ and $C_z$ compensation arrangements discussed in the following.

As carrier-wave frequency 450 c/s is chosen. This value is so low that the damping of the carrier wave in the cable can be made small enough to be neglected, and so high that the construction of an amplifier with the desired band width (namely twice the maximum modulation frequency of the carrier wave, *i.e.* the highest frequency occurring in the oscillogram) still offers no difficulties.

### *Time base and piston-stroke base*

A time-axis generator is included in the apparatus similar to that which is used in the cathode ray oscillograph recently described in this periodical [3]). With the sawtooth voltage given by this generator the cathode ray is given the necessary horizontal deflection to trace a pressure-time diagram. For tracing a pressure-volume diagram, however, the horizontal deviation of the fluorescent spot must be proportional at every moment to the displacement of the piston with respect to its position at the "dead point" near the top of the cylinder. The deflection voltage which is necessary for this is obtained by a "piston-stroke indicator" which functions as follows. A revolving cylinder of the shape shown in *fig. 5* is coupled to the crank shaft of the engine. Together with a fixed plate this cylinder forms a condenser whose capacity varies as the cylinder turns. By choosing a suitable shape for the cylinder the capacity of the cylinder condenser at every moment can be made proportional to the displacement of the piston. The cylinder condenser is included in a bridge connection in the same way as the membrane condenser of the pressure indicator, and the bridge is fed *via* a cable with the same high-frequency voltage. The output of the bridge is again amplified and rectified and applied to the horizontal deflection plates of the cathode ray tube. The piston-stroke indicator thus acts in exactly the same way as the pressure indicator itself (see also the diagram fig. 4).

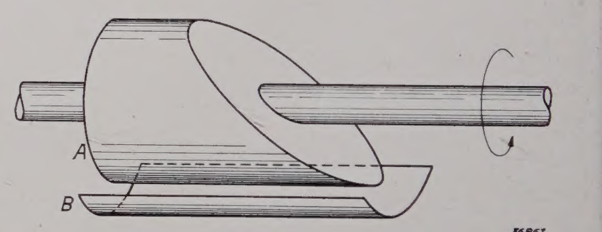


Fig. 5. Principle of the piston-stroke recorder. The cylinder *A* which is cut off in a certain way and coupled with the crank shaft, forms, together with the fixed counter electrode *B*, a condenser whose capacity varies as *A* rotates with the displacement of the piston in the cylinder of the engine.

[3]) A cathode ray oscillograph for use in tool making, Philips techn. Rev. 5, 277, 1940.

### Construction of the pressure indicator

Having given a general idea in the foregoing of the construction of the apparatus, we shall now give some details of the connections and of the construction of the components. Especially the pressure indicator deserves attention. It is a component which must satisfy rigid requirements in three respects: electrically, mechanically, and thermally. In the first place it may be noted that the capacity in the branch *bc* of the bridge (fig. 3) is composed of that of the membrane condenser $C_m$ and the capacity $C_p$, in parallel with it and independent of the pressure, between the counter electrode plus connections and earth. Since $C_p$ may vary somewhat due to different influences, especially temperature changes, it is necessary to keep $C_p$ as small as possible. To this end the connection is made as short as possible, *i.e.* the whole bridge is placed as close as possible to the membrane condenser. Nevertheless there still remains a considerable stray capacity of the enclosed counter electrode (fig. 2), so that $C_p$ could not be made smaller than about 18 $\mu\mu$F. In order to limit the influence of variations in $C_p$ one must therefore try to make the capacity $C_m$ which changes with the pressure as large as possible by making the air gap between membrane and counter electrode very small. In doing this, however, care must be taken that no short circuit can occur during use between the membrane and the counter electrode. Short circuiting was found to be promoted especially by the freeing of particles of material from the membrane — a phenomenon which need cause no surprise when it is remembered that the membrane may become red hot due to contact with the hot gases in the cylinder, and that it continually undergoes pressure shocks of up to 100 atmospheres. By careful ageing of the membrane, however, this phenomenon could be rendered harmless to such an extent that the air gap could be reduced to 0.2 mm. Since the area of the surface of the membrane was determined by the consideration that the pressure indicator should be able to be fastened into the wall of the cylinder in the same way as a sparking plug, the capacity of the membrane condenser was approximately determined at the same time. The value obtained is $C_m \approx 1.5$ $\mu\mu$F.

The relatively small values of $C_m$ compared with that of the stray capacity $C_p$ make it necessary to work with as large as possible capacity variations of the membrane condenser. The membrane is therefore so constructed that at the maximum pressure the displacement $f$ at the centre is almost equal to the width of the air gap, namely 0.18 mm. The tensile stresses hereby occurring in the membrane may not become too large. The following general relation holds for the maximum tensile stress $\delta_{max}$ in a circular membrane fastened around its circumference:

$$\sigma_{max} = K \frac{E}{c} f \nu_1 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Here $\nu_1$ is the lowest resonance frequency of the membrane, $c$ the velocity of sound in the material of the membrane, $E$ its modulus of elasticity and $K$ a constant which depends only upon the rigidity with which the membrane is clamped [4]). In our case the constant $K$ is approximately 4.5. When the values of $c$ and $E$ for steel: $c = 5 \times 10^5$ cm/s, $E = 20 \times 10^5$ kg/cm², are filled in, and for $\nu_1$ the value 25 000 c/s which is desired according to the above, then for $f = 0.18$ mm one arrives at a maximum tensile stress $\delta_{max} = 8\,000$ kg/cm².

With an ordinary good quality of steel this value is permissible. In our case, however, the unusual thermal load on the membrane had still to be taken into account. During combustion in the cylinder peak temperatures of 1 600° C occur, while the average working temperature of the membrane may amount to about 550° C. With ordinary kinds of steel the permissible value of $\delta_{max}$ thereby decreases very considerably, to only 2 000 kg/cm², for example. In order to be able to obtain the desired values of $f$ and $\nu_1$ and at the same time to ensure reliability in operation and sufficient constancy of the properties of the membrane, a specially tough and heat-resistant kind of steel was used and its yield value was further raised as much as possible by extra hardening.

In order to protect the membrane against becoming too hot, *i.e.* to limit the average temperature to the value of 550 °C already mentioned, a perforated cap is placed in front of it, see *fig. 6*. This helps to conduct the heat of the gases to the cooled walls of the cylinder, and at the same time supports the whole pressure indicator. The cap has an ex-

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4) If $p$ is the excess pressure, $r$ the radius of the membrane and $\delta$ its thickness, then

$$f = C_1 \frac{r^4}{\delta^3} \frac{p}{E}, \qquad \sigma_{max} = C_2 \frac{r^2}{\delta^2} p, \qquad \nu_1 = C_3 \frac{\delta}{r^2} c,$$

where $C_1$, $C_2$, $C_3$ are constants, which depend upon the rigidity of the fastening of the membrane. When the two last equations are divided by each other and the pressure $p$ eliminated, the dimensions $r$ and $\delta$ are also found to disappear from the resulting equation, and equation (1) is obtained where $C_2/C_1C_3$ is set equal to $K$. A similar relation is also found for other vibrating systems. This has already been pointed out in this periodical in connection with a discussion of the sound cutter of the Philips-Miller system: Philips techn. Rev. **1**, 136, 1936.

ternal screw thread like a sparking plug and is screwed into the wall of the cylinder. This construction has the advantage that the material in the neighbourhood of the point where the membrane is clamped is kept free of forces which occur during the screwing in (actually the membrane is not clamped but simply forms the bottom of the cylinder $B$). These forces would otherwise cause a deformation and in that way be able to change the sensitivity of the pressure indicator (*i.e.* its calibration).

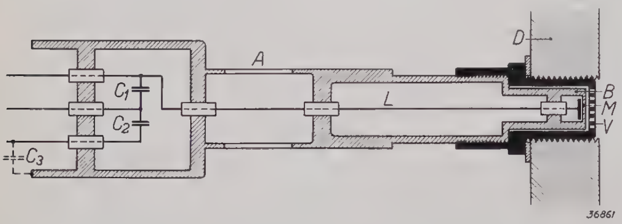



Fig. 6. Construction of the pressure indicator. The membrane $M$ forms the bottom of a cylinder $B$. $V$ perforated cap, $D$ cylinder wall, $L$ lead of the counter electrode, $C_1$, $C_2$, $C_3$ condensers of the bridge.

In the cross section sketch fig. 6 the condensers of the bridge may also be seen which is situated in the immedate neighbourhood of the membrane condenser. As already stated, it is by means of this precaution that the value of the stray capacity $C_p$, and with it the influence of its variations are kept small. On the other hand, however, this precaution introduced the danger that the impedances of the other bridge elements would vary much due to the vibrations and the transmission of heat from the engine cylinder, so that it would be a case of out of the frying pan into the fire. This could be avoided by a very compact and strong construction of the bridge with high-frequency porcelain used in most places for insulation, and by a heat insulating separation between the membrane condenser and the bridge. The section $A$ which supports the bridge is provided with holes so that only a small cross section is available for heat conduction and the air can flow freely through it, see *fig. 7*. Furthermore the whole rear section as well as the

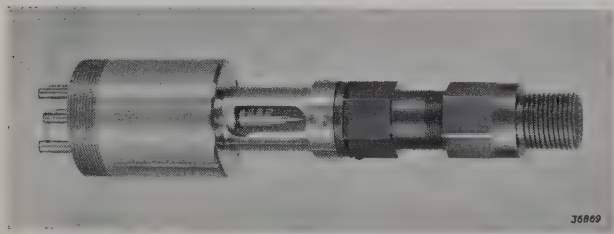



Fig. 7. Photograph of the pressure indicator. On the right the cap with sparking plug screw thread which is screwed into the wall of the cylinder. On the left the cable to the indicating instrument is connected and fastened.

connection $L$ is made of chrome-iron which is a poor heat conductor. In this way the bridge portion of the pressure indicator was kept at a temperature no higher than 50° C without a special water-cooling system being needed.

**Compensation arrangement**

The bridge can be brought out of equilibrium by an increase as well as by a decrease in the capacity of the membrane condenser. In both cases the amplitude of the high-frequency output voltage of the bridge will increase from zero to a certain value, and therefore a corresponding deviation of the fluorescent spot will appear on the screen of the cathode ray tube. This is made clear in *fig. 8a*. In order to obtain a linear relation between the pressure and the deviation on the screen, the bridge must be brought into equilibrium for such a low (or high) capacity $C_0$ that it never passes this equilibrium at any capacity variation occurring (*i.e.* at any pressure occurring).

Now, however, the following complication appears. The amplifier for the vertical deflection of the cathode ray can receive a high-frequency input voltage due to other causes besides capacity variations of the membrane condenser. In the first place the cables and transformers for leading in and leading out the high-frequency voltage of the bridge are always capacitively and inductively coupled to a certain extent, notwithstanding careful mutual shielding; the voltage thereby induced reaches the amplifier entirely outside of the bridge. The balance of the bridge, which requires not only a regulation of the effective capacities, but also of the loss resistances of the four condensers, is always more or less disturbed due to the fact that a drift in the value of the loss resistances caused by temperature influences can never entirely be avoided. This again results in a certain initial voltage at the input of the amplifier.

The different contributions to the total input voltage of the amplifier must be added vectorially since they may differ in phase. The magnitude of the resultant voltage vector determines the deviation of the fluorescent spot obtained. Suppose for instance that the initial voltage $E_1$ (made up of different contributions) is shifted 90° in phase with respect to those voltages $\Delta E$ which occur due to the pressure variations. The magnitude of the resultant vector $E$, and therefore also the deviation $y$ observed on the screen, then varies with the pressure according to fig. 8*b*; in the region of low pressures the diagram is somewhat compressed. An even greater distortion occurs when the vector

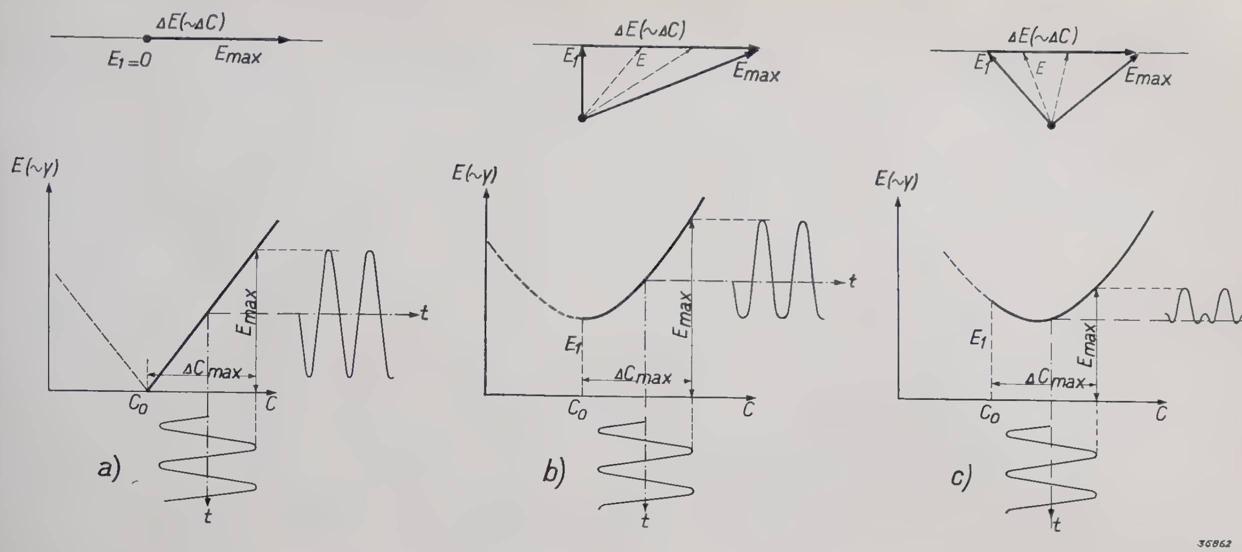



Fig. 8. Relation between the deviation $\gamma$ on the screen, which is proportional to the input voltage $E$ of the amplifier, and the capacity $C$ of the membrane condenser.
*a*) No undesired initial voltage $E_1$ at the input of the amplifier. At $C_3$ the bridge is in equilibrium. $C_3$ must lie outside the region in which $C$ varies with the pressure prevailing. Then $\gamma$ is a faithful representation of $C$ (thus of the pressure) as shown in the oscillogram constructed for a sinusoidal variation of $C$.
*b*) Undesired initial voltage $E_1$, shifted 90° in phase with respect to the voltage $\Delta E$ which is obtained by the capacity variations $\Delta C$. $\gamma$ is proportional to the magnitude of the resultant vector $E$. The oscillogram is flattened at the low-pressure values.
c) Arbitrary initial voltage $E_1$. The relation between $\gamma$ and $C$ is now no longer singular throughout the whole range of variations. In the oscillogram a reversing of the troughs as well as flattening may occur.

of the initial voltage $E_1$ has a direction like that indicated in fig. 8c. The magnitude of the resultant vector $E$ then varies according to the curve drawn, the relation between deviation and pressure is no longer singular in the whole range of pressures; with a sinusoidally varying pressure the troughs are reversed in the oscillogram (see the figure).

In order to avoid these deformations it is necessary to make the initial voltage $E_1$ at the input of the amplifier disappear. This has been made possible in a very simple way in the case of the indication here described: part of the oscillator voltage is fed directly to the amplifier, while phase and amplitude of this voltage are so adjusted that the initial voltage $E_1$ is exactly compensated.

Since the phase of the initial voltage $E_1$ may vary between 0 and 360°, the phase of the compensation voltage must also be able to be varied within these limits. The connections shown in *fig. 9a* are used for this purpose. They consist chiefly of two similar resistance bridges which are fed from the oscillator. The two supply voltages ($E_0$) differ 90° in phase. By moving contact *a* the voltage between *c* and earth can be regulated between $+E_0/2$ and $-E_0/2$. The same is true upon moving *g*, for the voltage between *e* and earth which differs by 90°. The vector of the resulting voltage between *c-e*, which is used for the compensation, can therefore take on any position within the square drawn in fig. 9*b*, *i.e.* the compensation voltage can be varied 360° in phase and at least between 0 and $E_0/2$ in amplitude.

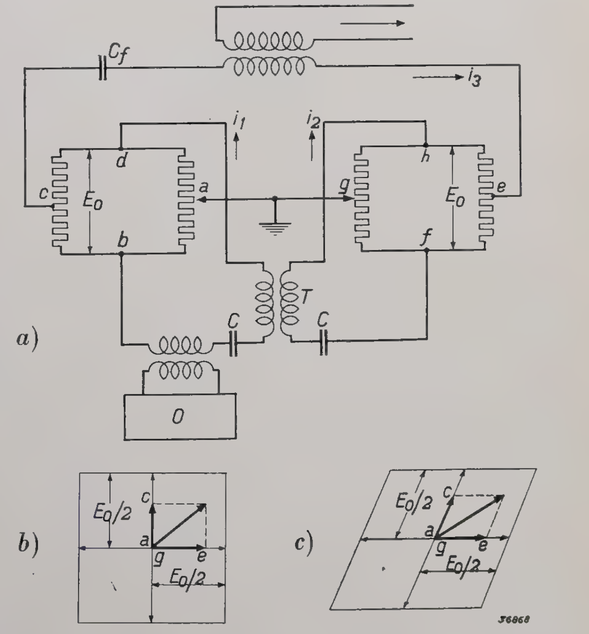



Fig. 9. Connections (*a*) consisting of two bridges *a-b-c-d* and *e-f-g-h* for obtaining the compensation voltage. By means of a condenser $C$ in each bridge, current and voltage are brought into phase. Since the secondary voltage of the transformer $T$ is always shifted 90° in phase with respect to the primary current, $i_1$ and $i_2$ are therefore shifted 90° in phase. The compensation voltage is taken off between *c* and *e*, and can be varied 360° in phase by moving the contacts *a* and *g*. This is shown in the vector diagram: *b*) for the case where the currents $i_1$ and $i_2$ differ exactly 90° in phase; *c*) for the case where this condition is not satisfied.

If an appreciable current $i_3$ is taken off between *c-e*, the phase relation between the currents $i_1$ and $i_2$ in the two bridges changes; instead of fig. 9*b* a vector diagram like fig. 9*c*, for instance, is obtained. The range of variation of the amplitude has here become smaller for some phase angles. This effect is found to reach a minimum at a certain phase relation between the current taken off and the voltage. This phase relation is realized by means of the condenser $C_f$.

Compensation takes place practically as follows. The initial voltage on the amplifier causes a certain initial deviation of the fluorescent spot. The contact *a* is now moved until this deviation is a minimum. The same is now repeated with contact *g*. In general, however, the deviation cannot be reduced to zero in this way, but can be again reduced by a further moving of *a*, etc. Further consideration shows that this alternate regulation of *a* and *g* converges rapidly.

In order to avoid all deformation the compensation voltage must be adjusted to an accuracy of several per mille. To attain this great accuracy of adjustment the potentiometers *b-a-d* and *f-g-h* (fig. 9*a*) are so constructed that in order to cover the region of regulation seven complete turns of the knob for that purpose are required.

## The amplifier

If it is necessary to be able to determine the indicated cylinder power directly by planimetry from the pressure-volume diagram obtained, there must be a linear relation between the deviation on the screen and the cylinder pressure. Now without special measures the relation between these two quantities is by no means linear. The deviation on the screen when a normal linear amplifier is used is indeed proportional to the capacity variation of the membrane condenser, this capacity variation is not, however, proportional to the pressure variation. Proportionality would only exist if the movements of the membrane were small compared with the width of the air gap — a condition which, according to the description given of the pressure indicator, is far from satisfied. The relation between the capacity of the membrane condenser and the pressure is shown in *fig. 10* for the range of variations for practical use.

In order nevertheless to obtain a linear relation between the deviation on the screen and the pressure it is obvious that an ordinary linear amplifier should not be used, but the amplification should be made to decrease with increasing amplitude of the input voltage (increasing capacity variation), in such a way that the deviation from linear variation shown in fig. 10 is just corrected. For this purpose, as in the case of automatic volume control in radio receiving sets [6]), part of the rectified output voltage of the amplifier is fed back to the grids of the amplifier valves (the amplifier contains two stages), so that the operating point on the characteristic, and at the same time the slope of the valves, is changed according to the magnitude of the input voltage. While without this amplification regulation the relation between the deviation on the screen and the pressure would have the shape of the full line curve of fig. 10, by means of the regulation the broken-line curve in the same figure is obtained. The remaining deviation from linearity is slight, the difference amounts to about 2 per cent of the maximum pressure at the middle of the whole pressure range, while without regulation it amounts from 10 to 15 per cent.

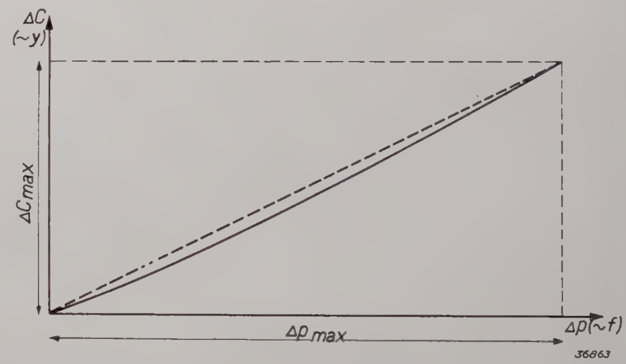



Fig. 10. Relation between the capacity $C$ of the membrane condenser and the pressure $p$ on the membrane. When a linear amplifier is used this is also the relation between the deviation $y$ on the screen and the pressure. By automatic regulation of the amplification the broken-line curve is obtained in its place.

Instead of "the whole pressure range" we might better speak of the variation range of the movement of the membrane. For different applications of the prssure indicator the pressure range will be very different; for these applications a series of pressure indicators have been developed which differ chiefly only in the thickness of the membrane, and in which, as a result, the maximum movement of the membrane (0.18 mm) occurs at different pressures, for instance at 30, 50, 100 atmospheres, etc. The variation of the capacity as a function of the movement is almost independent of the thickness of the

[5]) As a first, rough approximation we may consider the membrane condenser as consisting of two parallel plane plates whose separation diminishes with increasing pressure. With a small separation a given decrease in that distance will obviously cause a greater increase in capacity than with a large separation, which leads to the curvature of the full line in fig. 10.

[6]) A similar linearity correction has recently been described in this periodical for a density meter for X-ray films: Philips techn. Rev. 5, 333, 1940.

membrane, so that for all pressure indicators the same linearity correction can be used.

Although it is best always to use the pressure indicator which is adapted to the measuring range [7]), it may happen that the pressure varies less and that therefore the diagram only occupies a part of the screen of the cathode ray tube. In that case, in order to take advantage of the whole area of the screen, the sensitivity of the amplifier should be increased, which can be done by changing the bias of the control grid (the operating point) of the first amplifier valve with a potentiometer. Since when this is done one works with smaller capacity variations of the membrane condenser, and therefore with a smaller part of the full-line curve of fig. 10 which more nearly approaches linearity, the regulation range of the linearity correction must also be decreased, *i.e.* only a smaller fraction of the rectified output voltage must be fed back. This reduction is obtained by changing the fraction mentioned with a potentiometer which is coupled mechanically with the potentiometer for the regulation of the sensitivity.

According to fig. 8*a* the bridge is so balanced that the deflection voltage of the amplifier obtained becomes equal to zero for the smallest pressure occurring. In order to use the whole area of the screen, the fluorescent spot must be at the bottom of the screen at this pressure, it must therefore have a certain initial deviation. This is obtained by means of the output connections of the amplifier shown in *fig. 11.* The rectified output voltage, as

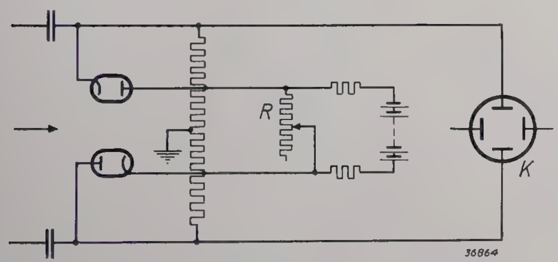



Fig. 11. Output connections (diagrammatic) of the amplifier for the vertical deflection voltage. The voltage rectified by the two diodes is fed in push-pull connection to the deflection plates of the cathode ray tube $K$, while by the likewise balanced bias on the resistance $R$ an initial deviation can be given to the fluorescent spot.

well as the constant extra voltage for the initial deviation, is applied to the deflection plates of the cathode ray tube in push-pull connection; this is necessary in order to avoid distortion of the oscillogram on the screen [8]). By short circuiting the resistance $R$ more or less the magnitude of the initial deflection can be further varied.

The band width of the amplifier which is tuned to the oscillator frequency of 450 c/s was fixed at 30 000 c/s. In the pressure diagrams of internal combustion engines it is unnecessary, as was explained at the beginning, to count on frequencies higher than 3 000 c/s, so that a band width of 6 000 c/s would be sufficient. Because of the higher value chosen, however, the pressure indicator can also be used for pressure measurements in quite different cases, namely for measuring fluid pressures in pressure lines of turbines, of hydraulic presses, etc. where considerably steeper pressure wave fronts (higher frequencies) occur than in engines cylinders.

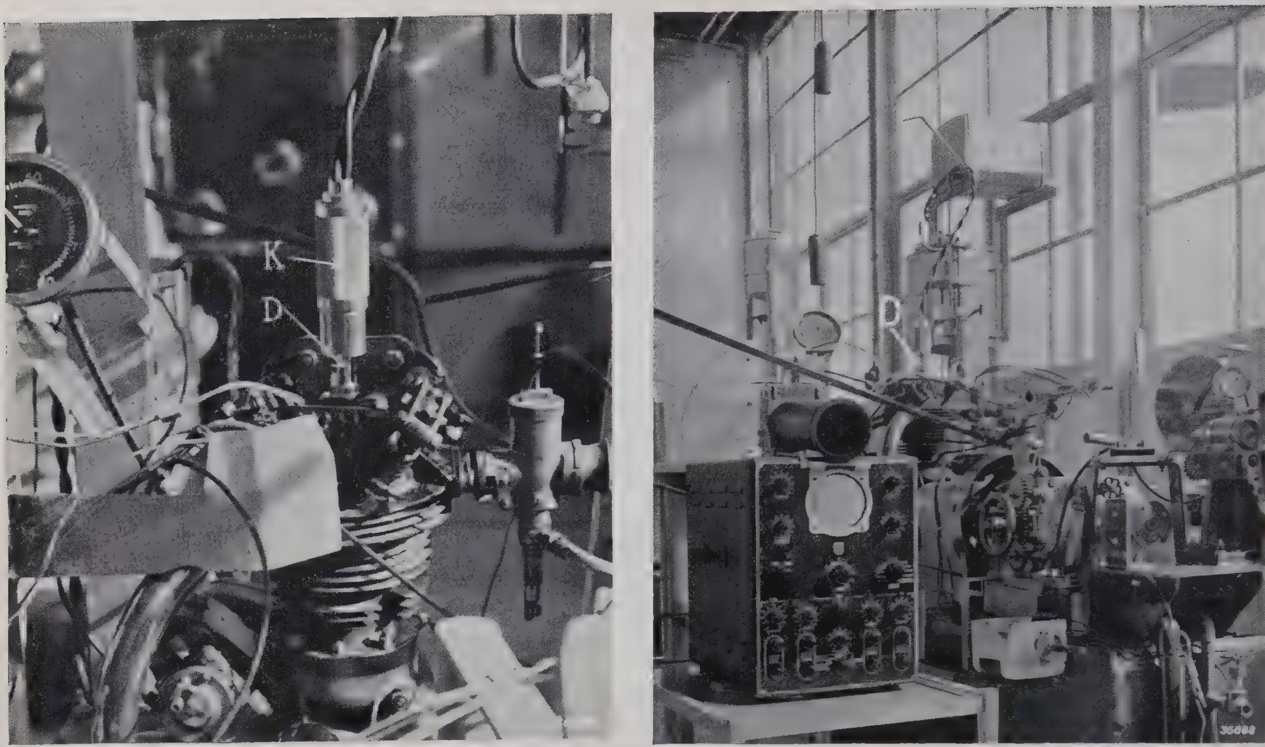
## Calibration and application of the indicator

It has already been pointed out that thanks to the carrier-wave principle chosen, static pressures can also be measured. The calibration is thus very simple: the pressure indicator is connected for instance to a cylinder with compressed gas whose pressure is regulated with a valve and read with an ordinary manometer. The modulus of elasticity of the material of the membrane is found to be practically independent of the temperature so that the calibration can be carried out with the membrane cold. The calibration is of course valid only for a given adjustment of the sensitivity of the amplifier. Furthermore it is valid only for a given amplitude of the carrier wave with which the bridge of the pressure indicator is fed. It is this amplitude which determines the proportionality factor between the input voltage of the amplifier and the capacity variation of the membrane condenser. In order to prevent changes in the carrier-wave amplitude which might occur due to voltage fluctuations of the mains from which the oscillator is fed, the feeding voltage of the latter is stabilized with neon lamps. At the same time this precaution serves to keep the carrier-wave frequency constant. If this frequency should change, the phase relation between the various voltage components at the input of the amplifier would change, and this would upset the compensation of the undesired initial voltage. For the rest, thanks to the carrier-wave principle, the whole arrangement is to a high degree insensitive to disturbances by induction from electric mains and the like.

In a coming article in this periodical the appli-

[7]) When this is done the sensitivity of the amplifier need only be small. The greater the sensitivity, the greater the displacement of the zero line obtained on the screen upon a drift in the bridge connections (fig. 8*b* and *c*).

[8]) This is for instance explained in Philips techn. Rev. 4, 198, 1939.




*a* *b*

Fig. 12. The pressure indicator GM 3 154 in operation. *a*) The pressure indicator *D* shown on the engine cylinder; *K* is the connecting piece for the 10 m cable connecting the pressure recorder to the indicating instrument. The latter may be seen in the left foreground of *b*).

cation of the apparatus for the investigation and control of internal combustion engines will be discussed in detail. We shall here merely draw attention to another possibility of application, namely the investigation of mechanical vibrations. If the membrane of the pressure indicator is omitted and the rigidly fixed counter electrode is placed opposite a vibrating body, the capacity between the electrode and earth varies, and the vibration becomes visible on the screen of the cathode ray tube. By giving the counter electrode suitable dimensions vibrations with amplitudes of several $\mu$ up to several cm can be measured. In the control of internal combustion engines also this possibility is important, namely for recording the so-called needle-stroke diagram.

*Fig. 12* shows the pressure indicator in use. In order to be able to compare various phenomena, for instance the variation in pressure in different cylinders, the apparatus is so arranged that three, different pressure (or vibration) recorders can be connected at the same time with cables. By a simple switching operation the three different diagrams can be made to appear on the screen in rapid succession. Since the required compensation voltage for the three cables plus pressure indicators will in general differ, each of the three connections is provided with its own compensation arrangement as in fig. 9*a*. A fourth compensation set is necessary for the amplifier of the horizontal deflection voltage (piston-stroke base). In fig. 12*b* may be seen the four pairs of regulation knobs of the compensation arrangements, placed at bottom of the panel of the cabinet.

# A VARIABLE AMPLIFIER VALVE WITH DOUBLE CATHODE CONNECTION SUITABLE FOR METRE WAVES

by M. J. O. STRUTT and A. van der ZIEL.

621.396.645.3.029.6

A great disadvantage of ordinary amplifier valves in the amplification of very high frequencies is the damping of the oscillator circuit connected with the control grid, due to the coupling between control grid circuit and anode circuit *via* the self-induction of the cathode connection. This disadvantage can be avoided by providing the cathode with two connections, which belong respectively to the control grid circuit and the anode circuit. By using these two connections of the cathode in a suitable manner numerous possibilities of connection occur so that it is possible to eliminate the damping of control grid circuit and anode circuit simultaneously, and at the same time to influence the reactance in a favourable manner. In this article a variable amplifier valve with a double cathode connection (EF 51) is described, which for wave lengths not shorter than 1.5 m gives approximately as satisfactory results as the (non-variable) push-pull amplifier valve EFF 50, and considerably better results than the existing button pentodes.

For the satisfactory performance of electronic valves which are intended for the amplification of very short waves it is essential that particularly the noise resistance, the input damping and the output damping should be low, while at the same time a steep slope must be retained. A steep slope, however, as explained previously in this periodical [1]), causes great damping of the input circuit due to the self-induction of the cathode connection. In the second article referred to, a valve was described in which this objection is met by the application of the push-pull principle. This valve, type EFF 50, can be used successfully for the amplification of signals with frequencies up to $6 \times 10^8$ c/s (wave length 50 cm), at which frequency an amplification by a factor 8 can still be obtained.

The principle upon which the push-pull amplifier valve is based consists in the fact that two systems which work in exactly opposite phase are connected to a common cathode connection. Since the sum of the high-frequency currents in the two systems is equal to zero, no high-frequency current flows through this cathode connection, and its self-induction can therefore have no damping effect on the input circuit.

The result obtained in this way answered fully to the expectations. In practice, however, it is not always possible to use a push-pull valve. It therefore became necessary to find out whether the aim in view — combatting the damping effect of the cathode connection — could not be attained by some other method as well.

A constructively simple principle, which offers many possibilities of influencing the input damping, the output damping and in addition the reactance in a favourable way, consists in the use of a double cathode connection. The anode current which returns to the cathode *via* one of the cathode connections then no longer needs choose a path which comprises part of the input circuit which is connected to the other cathode connection between grid and cathode (see *fig. 1b*).

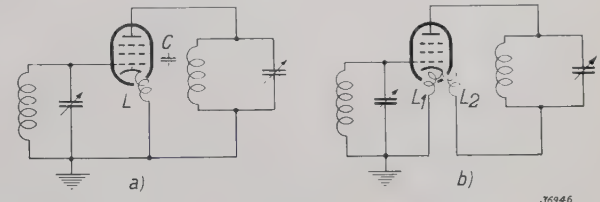



Fig. 1. Connections of a valve with single cathode connection (*a*) and of a valve with double cathode connection (*b*) in a stage for high-frequency amplification. Only the impedances important for high-frequency currents are given. In case *a* the self-induction *L* forms part of the input circuit and part of the output circuit at the same time, so that a back coupling occurs which is lacking in case *b*.

In order to show that by this means the damping effect of the anode current on the control grid circuit actually does disappear, we shall briefly review the theory of the input damping due to the self-induction of the cathode connection. If $v$ is the A.C. voltage on the input circuit of fig. 1$a$ and $i_a$ the anode A.C., then the A.C. voltage between control grid and cathode is approximately:

$$v_g = v - j\omega L\, i_a$$

and therefore the A.C., which will flow to the control grid due to the presence of the grid-cathode capacity $C$, amounts to

$$i_g = j\omega C\, v_g = j\omega C v + \omega^2 LC\, i_a$$

In the first approximation $i_a = Sv$ where $S$ is the slope of the valve, and therefore

[1]) M. J. O. Strutt and A. van der Ziel, The behaviour of amplifier valves at very high frequencies, Philips techn. Rev. 3, 103, 1938; A new push-pull amplifier valve for decimetre waves, Philips techn. Rev. 5, 172, 1940.

$$i_g = (j\omega C + \omega^2 LCS)\, v.$$

The second term in parentheses represents a current component which is in phase with the voltage, so that energy is taken from the input circuit. The equivalent input parallel resistance is

$$R_L = 1/\omega^2 LCS \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

(The subscript $L$ indicates that the self-induction of the cathode connection is the cause of the damping).

In the connections with two cathode connections given in fig. 1*b* the anode current has no effect on the voltage between control grid and cathode, so that the above-discussed damping effect is entirely absent.

We need not stop at this result, however, but by the addition of suitable circuit elements we may even obtain negative damping of the input circuit, as will be explained in the following. After having shown further that the output damping and the reactance can also be favourably affected by suitable use of two cathode connections, we shall describe the construction of a valve, namely the high-frequency amplifier valve EF 51 which, for waves no shorter than 1.5 m, possesses properties which are much more favourable than those of the existing button pentodes and only slightly less satisfactory than those of the push-pull amplifier valve EFF 50. Compared with the push-pull amplifier valve the new high-frequency valve has the advantage that it offers the possibility of varying the amplification by varying the slope of the valve.

**The influence of two cathode connections on the input damping**

For the sake of simplicity of expression in the following we shall define several of the terms to be used. By the first cathode connection we mean the cathode connection which belongs to the input circuit, while the second cathode connection belongs to the output circuit. The end of the cathode connection which extends outside the valve will be called the lower end; the upper end is thus connected to the cathode.

In order to profit by the double cathode connection for the purpose of decreasing the damping of the input circuit, another condenser $C_1$ must be added to the circuit elements given in fig. 1*b* between the lower end of the second cathode connection and the control grid. In this way the diagram of *fig. 2* is obtained. It is immediately clear that the A.C. voltage which occurs due to the self-induction of the second cathode connection, *via* the condenser $C_1$ will now lead to a grid A.C., as was the case in the ordinary connections according to fig. 1*a*. Since the condenser $C_1$ is connected to the lower end of $L_2$, however, this A.C. is opposite in phase to that which occurred in the case of fig. 1*a*, so that instead of a damping a negative damping is obtained.

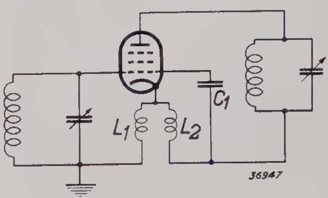



Fig. 2. Connection to two cathode connections and an auxiliary condenser $C_1$ for the purpose of eliminating the damping of the input circuit.

By analogy with equation (1) we obtain as value of the equivalent parallel resistance by approximation:

$$R_{L2} = -1/\omega^2 L_2 C_1 S \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This negative damping can be used for instance to decrease, or even entirely to eliminate the damping of the input circuit which occurs as a result of the finite transit time of the electrons between cathode and control grid [2]). This damping of the transit time, in the case of the valve EF 51 discussed later, corresponds approximately to a resistance

$$R_e = \frac{36}{f^2}\, 10^{-6}\, \Omega$$

where $f$ is expressed in megacycles per second. If we attempt to compensate this damping with the help of the negative damping action of the second cathode connection, the sum of the damping by $R_e$ and $R_{L2}$ must disappear as follows:

$$\omega^2 L_2 C_1 S = \frac{f^2}{36} \cdot 10^{-6} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The slope $S$ of the valve EF 51 amounts to about 10 mA/V. Moreover $\omega = 2\pi f \times 10^6$, so that for the unknown circuit elements $C_1$ and $L_2$ we obtain the condition:

$$L_2 C_1 = \frac{10^{-15}}{10 \cdot 36 \cdot 4\pi^2} = 7 \cdot 10^{-20} \text{ farad henry.} \quad (4)$$

If we choose for $C_1$ a capacity of 1 picofarad then the self-induction of the cathode connection $L_2$ must be $7 \times 10^{-8}$ henry, which is obtained by a wire about 6 cm long and 1 mm in diameter. We thus obtain elements which can easily be realized

[2]) See C. J. Bakker, Philips techn. Rev. 1, 171, 1936.

in practice. The damping elimination indicated is valid for the whole range of short waves, since the value of $L_2C_1$ determined by equation (4) is independent of the frequency.

### The influence of two cathode connections on the output damping

If in addition to the input damping we also wish to influence the output damping in a favourable direction, a second auxiliary condenser $C_2$ must be placed between the anode and the lower end of the first cathode connection (see *fig. 3*). If $e_a$ is the

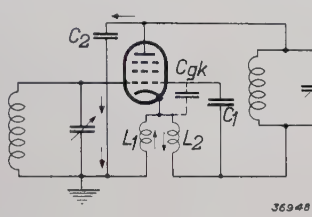



Fig. 3. Connection with two cathode connections and two auxiliary condensers $C_1$ and $C_2$ for the purpose of eliminating the input and the output damping. At the same time $C_2$ leads to a reactance capacity between anode and control grid, and thereby compensates the negative reactance capacity which is present at short waves due to other causes.

anode A.C. voltage over the oscillator circuit, then by approximation the following A.C. flows through this condenser:

$$i_{C_2} = e_a\, j\omega C_2,$$

along the path indicated by arrows *via* the self-inductions $L_1$ and $L_2$. Between cathode and earth therefore an A.C. voltage occurs:

$$v_k = -j\omega\, L_1\, i_{C_2} = e_a\, \omega^2\, L_1 C_2.$$

This change in the cathode potential leads to an extra anode current $-Sv_k$, thus $-e_a\,\omega^2 L_1 C_2 S$. From this it is evident that a negative damping also occurs in the anode circuit, which is determined by a formula quite analogous to the negative damping of the grid circuit.

In almost all connections occurring in practice the anode circuit of the high-frequency amplifier valve is coupled with the input circuit of a second stage, for instance a second amplifier valve or a mixing valve. The negative damping of the anode circuit is at the same time a negative damping of the input circuit of the following stage so that in the latter the damping need not be eliminated or only to a smaller extent.

### The influence of the two cathode connections on the reactance of the cathode on the control grid

As was stated in the discussion of the output damping, the A.C. voltage $e_a$ over the anode circuit leads to an A.C. along the path indicated by arrows (in fig. 3). This A.C. causes the A.C. voltage mentioned between cathode and earth:

$$v_k = e_a\, \omega^2\, L_1\, C_2$$

The A.C. flows further through the second cathode connection (self-induction $L_2$), so that the lower end of the latter possesses the following A.C. voltage with respect to earth:

$$v = e_a\, \omega^2\, (L_1 + L_2)\, C_2$$

These two A.C. voltages result in alternating currents to the control grid *via* the capacities $C_{gk}$ and $C_1$, respectively. These capacities connect the control grid to points on which an A.C. voltage acts which is in phase with the anode A.C. voltage, but which has a much smaller amplitude. The effect of the A.C. voltages $v_k$ and $v$ on the control grid circuit is therefore exactly the same as if the capacities $C_{gk}$ and $C_1$ were connected between control grid and anode, not with their whole magnitude, however, but reduced by a factor $v_k/e_a$ and $v/e_a$. The total apparent capacity hereby caused between control grid and anode thus amounts to:

$$C_{ag}' = C_{gk}\frac{v_k}{e_a} + C_1\frac{v}{e_a} =$$
$$= \omega^2 C_2\, [L_1\,(C_{gk} + C_1) + L_2 C_1] \quad . \quad . \quad (6)$$

This apparent capacity is now found to reduce the reactance at high frequencies, since the reactance already present due to other causes has at high frequencies the character of a negative apparent capacity [3]), which like that of equation(6) is proportional to the square of the frequency. The size of this apparent capacity $C_{ag}''$ depends upon the manner of connection, and at a wave length of 2 m, for example, may amount to 0.2 pF. This would correspond to a behaviour according to the formula

$$C_{ag}'' = -2.25 \cdot 10^{-19}\, \omega^2\ \mathrm{pF} \quad . \quad . \quad . \quad . \quad (7)$$

If the total reactance must just be made to disappear, care must be taken that

$$C_2 = \frac{2.25 \cdot 10^{-19}}{L_1\,(C_{gk} + C_1) + L_2 C_1} \quad . \quad . \quad . \quad (8)$$

The capacity $C_2$ to be calculated from this, as was already indicated in the previous section, gives at the same time a negative damping of the anode circuit; in the case of the valve EF 51 this is found to be more than enough to combat the causes of damping present.

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[3]) See the first article referred to in footnote [1]), p. 113.

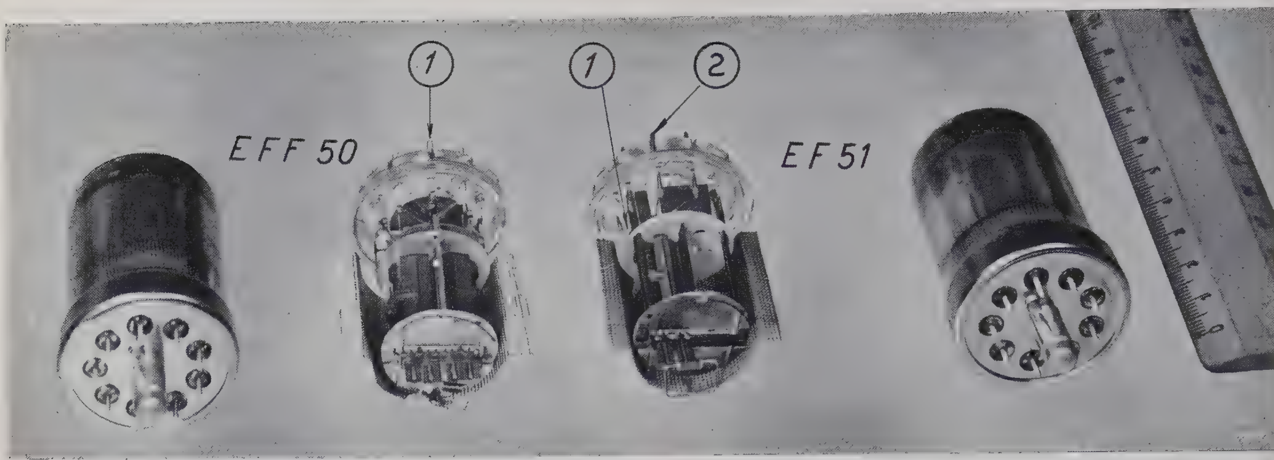


Fig. 4. Exterior and interior of the push-pull amplifier valve EFF 50, and of the valve with double cathode connection EF 51. The interior, from which the gauze screen has been removed, is mounted unsymmetrically in the case of the valve EF 51; *1* and *2* are the two cathode connections. In the case of the valve EFF 50 two identical systems are placed side-by-side and connected to a common cathode connection (*1*).

**Construction of the amplifier valve with double cathode connection**

In designing the amplifier valve with double cathode connection an attempt was made to make the harmful effect of the self-induction of the cathode connection as small as possible, even without the measures previously discussed. For this purpose the cathode connections, and particularly the first cathode connection, were kept extremely short, which could be done without changing the relative arrangement of the pins in the valve by placing the system unsymmetrically in the bulb, so that one end of the cathode falls exactly above the pin of the first cathode connection.

The construction of the valve with double cathode connection, type EF 51, is given in *fig. 4*. It may be seen that the appearance of this valve corresponds somewhat to that of the push-pull amplifier valve EFF 50 which is shown for the sake of comparison. In the case of the valve EF 51 the two cathode connections marked by arrows *1* and *2* may be distinguished; in the case of the push-pull amplifier valve, on the other hand, the two systems have a common cathode connection which is indicated by *1* in the photograph of the internal system.

The control grid of the valve EF 51, contrary to the case with EFF 50, has an irregular pitch (see *fig. 5*). In this way the magnitude of the negative control grid voltage, which is necessary to suppress the anode current, is made different for different parts of the cathode. In *fig. 6* it may be seen what effects this has on the characteristic. In the case of the valve EFF 50 the anode current is practically entirely suppressed by a control grid voltage of —6 V, and slightly above this "cut off voltage" the slope of the $I_a$-$V_g$ characteristic (slope $S_1$ in fig. 6) decreases very sharply with falling control grid voltage. In the valve EF 51, on the other hand, the cut off voltage is different from point to point, in other words, the cutting off takes place quite gradually. The result is that the change in the slope also takes place quite gradually. Thanks to this property of the EF 51 it is possible to regulate the amplification of the valve by changing the grid bias, without experiencing much difficulty with non-linear distortion.

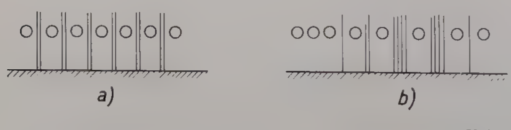


Fig. 5. *a*) Regular (*b*) irregular pitch of the control grid. For a control grid voltage in the regulation region the emission of the cathode is suppressed locally in the case of the irregularly wound grid.

The non-linear distortion is characterized in fig. 6 by the quotient $S_3/S_1$. The coefficients $S_1$ and $S_3$ are thereby derived from the series:

$$S \doteq S_1 + S_2 (V_g - V_{g0}) + S_3 (V_g - V_{g0})^2 + \dots$$

which represents the behaviour of the slope $S$ in the neighbourhood of the operating point (grid voltage $V_{g0}$). The strength of the cross modulation and of certain other undesired phenomena is found to be directly proportional to $S_3/S_1$ [4]), so that it is desirable to have this quotient as small as possible. As may be seen in fig. 6, $S_3/S_1$, in the case of the

[4]) On this subject we refer the reader to the book: Moderne Mehrgitter-Elektronenröhren, by M. J. O. Strutt, Springer (Berlin), 2nd edition 1939, p. 17.

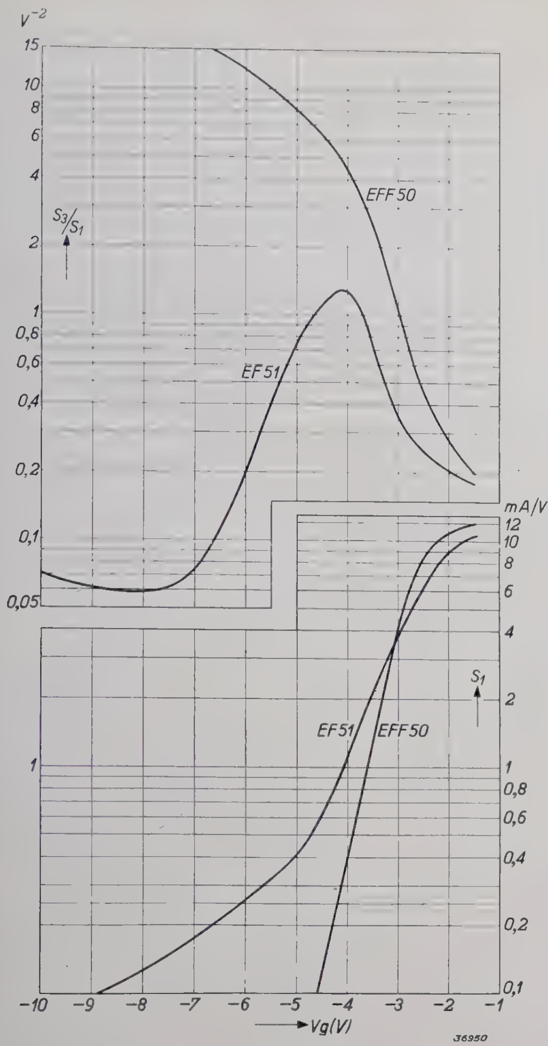


Fig. 6. Slope $S_1$ and distortion factor $S_3/S_1$ as a function of the grid voltage for the push-pull amplifier valve EFF 50 and for the valve with double cathode connection EF 51. The factor $S_3/S_1$ in the case of the valve EF 51, especially for large negative control grid voltages, is much smaller than in the valve EFF 50.

valve EF 51 is much smaller, especially for large negative grid voltages, than in the valve EFF 50.

Like all amplifier valves, the valve EF 51 exhibits a change in the input capacity upon regulation. This capacity variation may be unfavourable since due to it a detuning of the input circuit occurs. If only one cathode connection is used this capacity variation can for the most part be compensated in a simple way, for instance by the introduction of a resistance of about 30 ohms in this cathode connection. If both cathode connections are used the connections undergo several additional alterations.

The screen grid of the valve with double cathode connection is wound with a lower pitch than that of the push-pull amplifier valve. By this means the static capacity between control grid and anode is reduced and the internal resistance enlarged, which means an improvement of the valve qualities especially for not very short waves. In the following table the most important properties of the button pentode, the push-pull amplifier valve and the new amplifier valve with double cathode connection are shown side-by-side.

**Table I**

Properties of amplifier valves for very short waves.

| Valve type | Button pentode 4 672 | Push-pull amplifier valve EFF 50 | Valve with double cathode connection EF 51 |
|---|---|---|---|
| Slope (mA/V) | 1,4 | 11* | 10 |
| Noise resistance $R_r$ (ohms) | 8 000 | 600* | 900 |
| Damping resistance $R_e$ for $\lambda = 3$ m (ohms) | 18 000 | 2 700* | 3 600 |
| $R_r/R_e$ | 0.44 | 0.22 | 0.25 |
| $C_{ag}$ for low frequencies (pF) | < 0.007 | < 0.02 | < 0.006 |

*) Per system (the valve contains two identical systems).

**) By this is meant the input parallel resistance which is equivalent to the damping due to the transit time of the electrons between cathode and control grid.

The noise qualities of the different valves are characterized in the table by the ratio between the socalled noise resistance $R_r$ and the damping resistance $R_e$ which occurs at the input side of the amplifier valve due to the finite transit time of the electrons between cathode and control grid. This quantity $R_r/R_e$ is found in many practical cases to determine the maximum attainable ratio between signal voltage and noise voltage. From table I we see that the valve EF 51, as far as noise is concerned, is almost as good as the valve EFF 50 and considerably better than the button pentode 4 672.

## Application of the valve with double cathode connection

The amplifier valve with double cathode connection will be used in the first place for the amplification of ultra short waves to a lower limit of 1.5 metres. These waves are of great importance, for example for telephony with directional aerials and possibly for television; in addition these frequencies are encountered as intermediate-frequency in superheterodyne receivers for still shorter waves.

The connections of the amplifier valve with double cathode connection can be based upon the diagram given in fig. 2, for example. This scheme

[5]) The capacity $C_1$ in many cases need not be realized by a separate condenser, but can be obtained by using the capacity between control grid and screen grid present in the valve. For this it is necessary that the screen grid should be connected for high frequency to the end of the second cathode connection, as is the case in the connections given in fig. 7.

is valid only for high-frequency currents, and must still be supplemented by the connection lines necessary for obtaining the desired biases of the different electrodes. In this way a scheme is arrived at like *fig. 7*, the functioning of which will be clear after the discussion of fig. 2.

If an attempt is made to apply these connections to practical cases, difficulties are found to occur due to parasitic capacities. The oscillation circuit $LC$ in the anode circuit usually has a fairly considerable capacity with respect to earth or with respect to the chassis, and this capacity is in parallel with the capacity $C_2$. We have seen that $C_2$ causes a reaction which need only be very small to eliminate the small negative reactance present. If $C_2$ becomes too great a positive reactance occurs which, like the negative reactance, may have unfavourable effects on the amplification, for instance, a tendency to oscillation [6]). Therefore with these connections it is necessary to reduce the parasitic capacity between the oscillating circuit and earth, which can be done by housing the oscillating circuit in a closed container connected to the second cathode connection, as indicated in the figure.

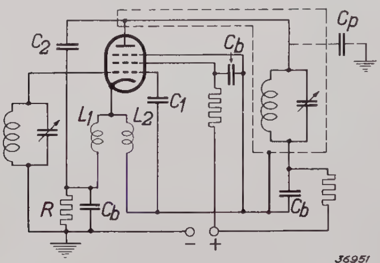


Fig. 7. Complete connections of a high-frequency amplifier stage with the valve EF 51 as amplifier valve. In order not to make the capacity $C_2$ too large due to the parasitic capacity $C_p$, the output circuit must be shielded. $C_b$ block condensers. The resistance $R$ serves to obtain the negative control grid bias.

If no other amplifier stage follows the connections just discussed, the method of shielding indicated can easily be realized. If, however, there are a number of stages in cascade, this is practically impossible. The anode A.C. voltage of the first valve must always be transmitted to the control grid of the following valve, which itself already possesses a capacity of about 10 pF with respect to earth.

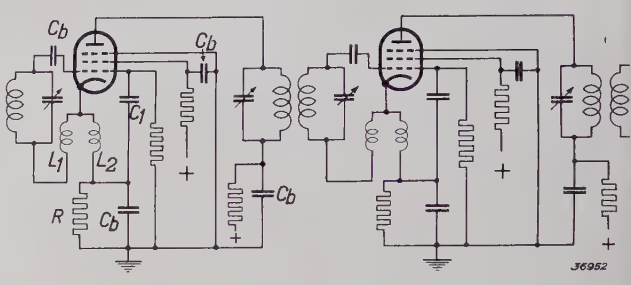


Fig. 8. Connections with the valve EF 51 in which no shielding of the output circuit is necessary. By inductive coupling any desired number of stages of this kind can be connected in succession. $C_b$ block condensers. The resistance $R$ serves for obtaining the negative control grid bias.

In order to be able to form cascade connections, therefore, it is desirable to use a connection with which no shielding of the anode circuit with respect to earth is necessary. Such a connection can be obtained very simply by connecting the second cathode connection in fig. 2, instead of the first, to earth. The scheme of connection thus obtained may be seen in *fig. 8*; it is also shown in this figure how by the use of an inductive coupling a second identical amplifier stage may be connected to the first stage. In this way any desired number of amplifier stages can be connected in succession. Instead of the magnetic coupling, electrostatic coupling can also be applied as shown in *fig. 9*. In this case two coupling condensers are required to take off the A.C. voltage to be transmitted from the two ends of the oscillation circuit. Apart from this the connections show no fundamental difference from the ordinary coupling with normal valves between successive stages.

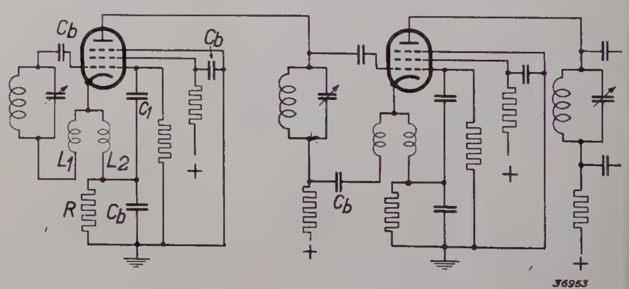


Fig. 9. Like fig. 8, but with a capacitative coupling between the stages.

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[6]) On the disturbing effect of reactance see the article on transmitting pentodes, Philips techn. Rev. 2, 257, 1937, especially fig. 3 and page 261.

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